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Environmental Effects of Dredging Technical Notes

PREDICTING AND MONITORING DREDGE-INDUCED DISSOLVED OXYGEN REDUCTION

PURPOSE: This note summarizes the results of research into the potential for dissolved oxygen (DO) reduction associated with dredging operations. Efforts toward development of a simple computational model for predicting the degree of dredge-induced DO reduction are described along with results of a monitoring program around a bucket dredge operation.

BACKGROUND: The biological impact of dredge-induced DO reduction is sometimes cited as a concern by resource management agencies, as was the case with fishery resource managers presented with a proposal to dredge the Haverstraw Bay portion of the Hudson River Estuary from August through October 1987. Haverstraw Bay is a shallow (2.5 to 3.0 m), wide (5 km) reach of the Hudson River and is an important nursery area for several species of anadromous fishes, including striped bass, *Morone saxatilis*, the juveniles of which congregate in the shoals during late summer-early fall. The New York District and the US Army Engineer Waterways Experiment Station responded to the concern by constructing and applying two simple computational models for predicting the effect of a dredging operation on DO concentrations. A monitoring study was designed and conducted to measure actual dredge-induced DO reduction in Haverstraw Bay and compare these values to those predicted by the models (Lunz, LaSalle, and Houston 1988). A description and comparison of the models and the results of the monitoring program are the subjects of this note.

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Introduction

Previous information on direct measurements of dredge-induced reduction in dissolved oxygen (DO) is limited to three studies: a bucket dredging project in a highly industrialized channel in New York (Brown and Clark 1968), a cutter-head dredge operation in Grays Harbor, WA (Smith et al. 1976), and a hopper

dredging project in a tidal slough in Oregon (US Army Engineer District, Portland 1982). Dredge-induced oxygen depletion in the 10-m-deep New York channel ranged from 16 to 83 percent in the mid to upper water column and up to 100 percent in near-bottom layers during placement under conditions involving poor tidal flushing, heavy industrial pollution, and generally low ambient DO levels. Periodic reduction of bottom water DO (up to 2.9 mg/ℓ) was observed in Grays Harbor. Dredge-induced DO reduction (1.5 to 3.5 mg/ℓ) at the 10-m-deep Oregon site (background levels ranging between 3.6 and 6.6 mg/ℓ) was limited to slack-water conditions in the bottom one-third of the water column lasting until tidal flow resumed (within 2 hr). DO levels increased above ambient (by 2.0 mg/ℓ) during dredging under flood tide conditions.

The effect of dredging on DO was studied through modeling designed to estimate DO reduction based on site-specific sediment characteristics (Lunz, LaSalle, and Houston 1988) along with a monitoring program to measure near-field (within 400 m) and far-field (bay-wide) DO conditions around an operating bucket (Houston, LaSalle, and Lunz in preparation). The models described here represent a series of attempts at understanding the cause-and-effect relationships between sediment characteristics and DO depletion.

Basis for the Models

The approach toward modeling dredge-induced DO reduction assumed that reduction was related to the oxygen demand of the sediment being dredged, concentration of sediment suspended by the dredge, and time period that a parcel of water would be exposed to the suspended sediment field around the dredge. Information about the levels of suspended sediments known to occur around operating dredges is readily available (Hayes, Raymond, and McLellan 1984, Hayes 1986, and Havis 1988). The differences between models, therefore, involved different approaches toward estimating oxygen demand of the sediment and the timespan over which these reactions occur.

An initial effort at developing a model of DO reduction (Lunz and LaSalle 1986) used varying estimates of suspended sediment concentrations (100 to 500 mg/ℓ) and estimates of low, moderate, and high benthic oxygen demand (5, 20, and 150 $\mu\ell$ DO/g sediment dry weight) applied to a hypothetical closed cylinder of water for 1 hr. This model predicted minimal depletion, ranging from 0.01 to 0.11 mg/ℓ. The more recent modeling efforts in Haverstraw Bay

(Lunz, LaSalle, and Houston 1988) reflected more refined views of the relationships between sediment compounds and oxygen demand and the timespan over which these reactions occur. Specifically, estimates of oxygen demand were based on site-specific measurements of selected sediment compounds. Estimates of the suspended sediment concentrations in the dredge plume were taken from a study of a bucket dredge operation reported in Bohlen, Cundy, and Tramontano (1979).

Model A used oxygen demand (OD) rates estimated from existing data on the relationship between benthic oxygen demand (4-day BOD) and volatile solids (VS) concentrations reported for the Connecticut River (Issac 1965) to generate a regression equation that predicted OD. Choice of OD as a function of VS was based on a body of literature relating benthic oxygen demand and VS concentrations (see review in Lunz and LaSalle 1986). The use of BOD estimates, however, assumed that OD was a function of both chemical and biological processes acting over a period of days (in this case, 4 days). Volatile solids concentration was estimated from measurements of actual total organic carbon (TOC) in Haverstraw Bay sediments, assuming 100 percent volatilization. DO reduction was assumed to occur over days, reflecting the passage of a parcel of water through a circular dredge plume with varying suspended sediment concentrations with distance from the dredge. The form of the equation was:

$$\underset{(\text{mg DO}/\ell)}{\text{Oxygen Reduction}} = \underset{(\text{mg sed}/\ell)}{\text{Sediment Conc.}} \times \underset{(\text{mg TOC/mg sed})}{\text{Total Organic Carbon Conc.}} \times \underset{(\text{mg DO/mg VS}/4\text{ days})}{\text{Oxygen Demand}} \times \underset{(\text{days})}{\text{Residence Time}}$$

With a mean VS concentration of 1.1 percent, oxygen demand was estimated to be 0.008 mg DO/mg VS/4 days (estimated from the equation, 4-day-BOD (mg DO/mg VS) = 7.2 VS, calculated through the origin and based on data in Issac 1965). Residence time of a parcel of water within the dredge plume (2 days) was calculated using data on flow rate (11.3×10^6 m^3/day) and cross-sectional area of the bay (76,992 m). DO reduction was calculated within each of three subportions of a hypothetical circular dredge plume (radii of 100, 1,000, and 1,500 ft), within which suspended sediment concentrations were set at 400, 200, and 100 mg/ℓ, respectively (Bohlen, Cundy, and Tramontano 1979). Application of these parameters led to a predicted DO depletion of less than 0.1 mg/ℓ over a 4-day period (a liberal estimate of residence time). Actual estimates of 4-day BOD for site-specific sediment samples, however, gave a mean value for OD of 0.10 mg DO/mg

TOC/4 days (n = 3), leading to a total 4-day estimate across the plume of 0.8 mg DO/ℓ.

Model B assumed that OD of the sediment being resuspended is largely an immediate, short-term phenomenon (analogous to immediate dissolved oxygen demand or IDOD), attributable to the chemical reactions of the most frequently encountered, readily oxidizable, chemical compounds (i.e., ferrous iron and free sulfides) found in most marine and estuarine sediments. The model assumed that the chemical reactions are rapid (on the order of minutes) and that all of the available compounds become fully oxidized upon suspension in the water column, thereby eliminating the need to consider duration of suspension. Dissolved oxygen reduction was estimated as the amount of DO needed to fully oxidize the material suspended by using stochiometric equivalents for oxidative reaction of these materials at site-specific concentrations. The form of the equation was:

$$\begin{array}{c}\text{Oxygen}\\ \text{Reduction}\\ (\text{mg DO}/\ell)\end{array} = \left[\begin{array}{c}\text{Sediment}\\ \text{Conc.}\\ (\text{mg sed}/\ell)\end{array} \times \begin{array}{c}\text{Iron Conc.}\\ (\text{mg Fe/mg sed})\end{array} \times \begin{array}{c}\text{Stochiometric}\\ \text{Equivalent of Fe}\\ (\text{mg DO/2.327 mg Fe})\end{array}\right] + \left[\begin{array}{c}\text{Sediment}\\ \text{Conc.}\\ (\text{mg sed}/\ell)\end{array} \times \begin{array}{c}\text{Sulfide Conc.}\\ (\text{mg S/mg sed})\end{array} \times \begin{array}{c}\text{Stochiometric}\\ \text{Equivalent of S}\\ (\text{mg DO/0.501 mg S})\end{array}\right]$$

Using mean values of ferrous iron (274.2 ng/mg sediment, n = 11) and free sulfides (1,582.6 ng/mg sediment, n = 11) for Haverstraw Bay sediments, the model predicted DO reductions of 0.3, 0.6, and 1.6 mg/ℓ at suspended sediment concentrations of 100, 200, and 500 mg/ℓ, respectively.

Monitoring Protocol

DO, temperature, and optical turbidity (surface, middepth, and near-bottom) were measured daily in the immediate vicinity (near-field) of the dredge (within 400 m) and weekly across the bay (far-field). Daily monitoring was conducted during periods of lowest expected DO concentrations (sunrise and next slack tide). Measurements were taken at four equidistant stations around the dredge, located 300 ft (91 m) upstream, downstream, and to either side. Two additional stations were located 600 ft (183 m) and 1,200 ft (366 m) downstream from the dredge. A reference station was located outside the dredging area (near the upstream extent of the existing navigation channel). Whether the dredge was

operating at the time of each collection was noted, allowing for comparison of dredging and nondredging periods. Weekly monitoring was conducted at 16 stations positioned along three cross-bay transects (Figure 1) and included predredging (3 weeks), dredging (5 weeks), and post-dredging (2 weeks) periods.

Data on the daily deviation of DO concentrations (relative to the reference site) for the most frequently observed worst-case combination of time-of-day and tidal condition (sunrise/ebbing) are summarized in Table 1. For comparative purposes, stations are arranged in order of greatest to lowest theoretical effect on DO reduction based on proximity to the dredge. Observations were recorded for both dredging and nondredging periods.

No statistical differences (Mann-Whitney test, alpha = 0.05) were detected between dredging and nondredging periods for any station or depth of collection. Considerable variation in DO concentration was observed for non-dredging periods

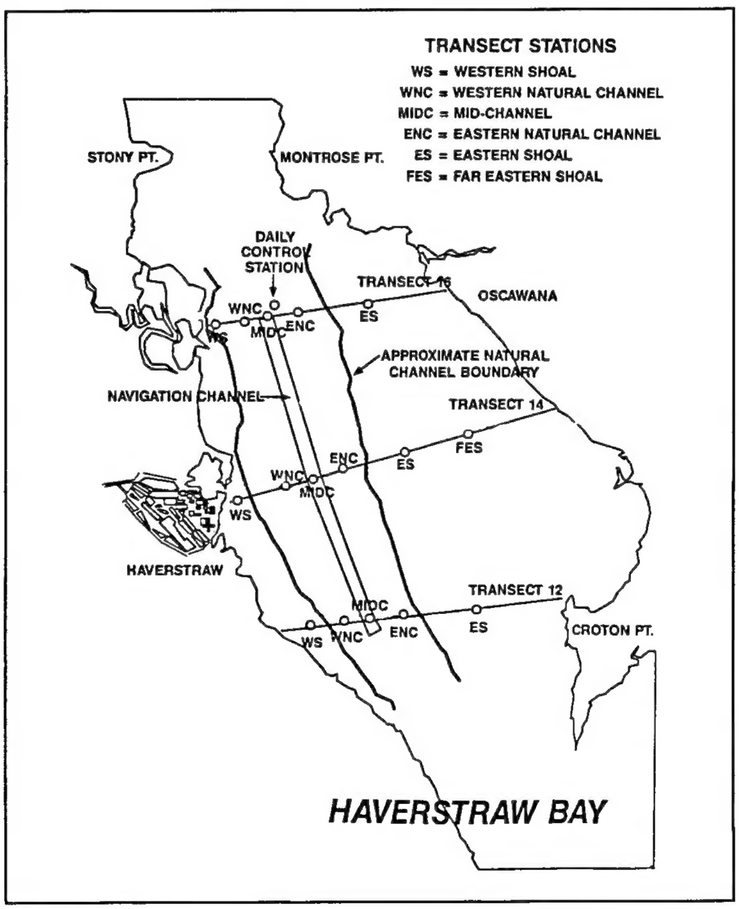

Figure 1. Weekly monitoring transect and station locations in the Haverstraw Bay portion of the Hudson River, New York

Table 1

Mean Deviation in DO Concentration (mg/ℓ), Relative to Reference at Six Locations around a Bucket Dredge during (n = 4) and without Dredging (n = 16) and the Difference Between Dredging and Nondredging

Depth	Operational Status	91 m Down	91 m Lateral	91 m Lateral	91 m Up	183 m Down	366 m Down
Surface	Dredging	-0.08	-0.13	-0.03	-0.20	0.00	-0.13
	Nondredging	-0.18	-0.16	-0.13	-0.10	-0.16	-0.15
	Difference	+0.10	+0.03	+0.10	-0.10	+0.16	+0.02
Middepth	Dredging	-0.10	-0.15	-0.10	-0.23	-0.05	-0.05
	Nondredging	-0.20	-0.14	-0.04	-0.12	-0.11	-0.14
	Difference	+0.10	-0.01	-0.06	-0.11	+0.06	+0.09
Bottom	Dredging	-0.23	-0.13	-0.15	-0.15	-0.10	-0.08
	Nondredging	-0.12*	-0.08	-0.02	-0.03**	-0.04	+0.01
	Difference	-0.11	-0.05	-0.13	-0.12	-0.06	-0.07

Note: Values are for observations made at sunrise, under ebbing tide conditions (from Lunz, LaSalle, and Houston 1988).
* n = 15.

ranging from +0.7 to -0.9 mg/ℓ for surface, +0.3 to -0.8 mg/ℓ for middepth, and +0.3 to -0.6 mg/ℓ for bottom measurements. Reference station variability was often greater than that observed near the dredge. Variation in DO during dredging ranged from +0.4 to -0.6 mg/ℓ for surface, +0.2 to -0.5 mg/ℓ for middepth, and +0.2 to -0.6 mg/ℓ for bottom measurements. Although mean deviations between dredging and nondredging were not significant, the 91 m upstream and downstream stations appeared to be most affected by the dredge. Maximum deviations in DO concentrations, however, were generally less than 0.20 mg/ℓ. Associated data on optical turbidity near the dredge showed levels generally at or below 10 NTU's (equivalent in this system to about 26 mg/ℓ) in the surface and middepth levels to as high as 40 NTU's (equivalent to about 140 mg/ℓ) in bottom waters.

Weekly data on DO and temperature from transect collections were used to calculate percent saturation values which allowed for comparisons of predredging, dredging, and postdredging periods (Table 2). Only near-bottom stations were analyzed (most likely to be affected). Percent saturation was above 70 percent

Table 2

Mean Values (Standard Deviation) of Percent Dissolved Oxygen Saturation at Weekly Transect Stations for Predredging (3 weeks), Dredging (5 weeks), and Postdredging (2 weeks) Periods and the Maximum Difference Between Dredging and Pre- or Postdredging Periods

Transect	Station	Predredging	Dredging	Postdredging	Difference
16	WS*	86.0a** (4.8)	76.1b (4.1)	85.9a (0.4)	9.9
	WNC*	80.2ab (1.3)	74.1a (4.6)	83.7b (3.3)	9.6
	MIDC	77.9 (1.5)	74.2 (7.3)	85.2 (5.3)	11.0
	ENC*	79.9ab (1.3)	73.8a (5.9)	85.2b (2.6)	11.4
	ES	87.8 (9.9)	77.3 (5.7)	83.3 (6.6)	10.5
14	WS	82.8 (2.0)	74.8 (5.8)	82.9 (2.3)	8.1
	WNC	78.6 (7.8)	74.2 (4.8)	81.6 (1.1)	7.4
	MIDC	76.0 (6.9)	73.5 (6.7)	81.1 (0.4)	7.6
	ENC	82.7 (2.8)	73.3 (7.6)	81.2 (1.7)	9.4
	ES	82.3 (1.1)	77.7 (7.2)	86.9 (0.3)	9.2
	FES	104.9 (28.9)	78.4 (8.3)	86.1 (2.2)	26.5
12	WS*	93.4a (13.6)	72.8b (10.1)	83.8ab (0.8)	20.6
	WNC	84.3 (4.2)	72.1 (7.8)	80.6 (2.5)	12.2
	MIDC	75.9 (9.8)	73.3 (8.5)	76.8 (8.1)	3.5
	ENC	84.0 (1.6)	72.6 (7.3)	71.8 (16.6)	11.4
	ES	92.5 (9.7)	81.3 (6.1)	73.2 (14.8)	11.2

Note: WS = western shoal, WNC = western natural channel, MIDC = midchannel, ENC = eastern natural channel, ES = eastern shoal, and FES = far eastern shoal.

* Significant Kruskal-Wallis test, H(0.05,5,3,2) = 5.25.

** a,b--means with no letters in common are significantly different (nonparametric Tukey test, Q(0.05,3) = 2.394).

during dredging and 80 percent during both pre- and post-dredging periods with an overall trend of lower saturation during the dredging period (by 3.5 to 26.5 percent). Significantly lower values, however, were detected for only 4 of the 16 stations. The average maximum difference between dredging and either pre- or postdredging periods was 11.4 percent, which, within the range of temperature occurring during the dredging period (13° to 28° C), would equate to a reduction in DO of from 0.9 to 1.1 mg/ℓ. DO levels remained above 6.0 mg/ℓ throughout the study period, and considerable variation in DO and percent saturation was observed at most stations during each sampling period.

There was a concomitant increase in turbidity during the dredging and post-dredging periods (Table 3), ranging from 3.9 to 13.5 NTU. Significant differences were detected for 7 of 16 stations. In contrast to percent saturation of DO, turbidity levels remained elevated after dredging ceased.

Conclusions

The underlying differences between these models of DO reduction involve the timeframe over which DO reduction takes place and the associated substrates and chemical/biological processes which would act within that time-frame. For Model A, DO reduction is based on the action of biological agents acting on volatile solids over the course of days. On the other hand, Model B is based on the immediate oxygen demand created by the rapid (within seconds or minutes) oxidation of iron and sulfides which ends once all the material is oxidized and the suspended sediment moves away or settles. The second model's approach reflects a more realistic scenario of actual processes around an operating dredge where anoxic sediments (and associated reduced compounds) remain in suspension for only a short period of time. If, however, fine organic materials remain in suspension for a period of days, as suggested from monitoring of bay-wide turbidity (Table 3), Model A may explain longer term conditions (days).

Near-field DO conditions measured around a dredge (Table 1) are within the range predicted by Model B at the levels of turbidity measured (10 to 40 NTU = 26 to 140 mg/ℓ sediment). At these suspended sediment levels, Model B would predict DO depletion of from 0.1 (26 mg/ℓ) to 0.5 mg/ℓ (140 mg/ℓ). Actually, DO depletion ranged from 0 to 1.0 mg/ℓ with a number of measurements showing greater DO (up to 0.3 mg/ℓ). Mixing, not accounted for in the model, may have acted to

Table 3

Mean Values (Standard Deviation) of Optical Turbidity (NTU) at Weekly Transect Stations for Predredging (3 weeks), Dredging (5 weeks), and Postdredging (2 weeks) Periods

Transect	Station	Predredging	Dredging	Postdredging	Difference
16	WS*	4.5a** (4.5)	9.5ab (9.5)	12.5b (0.7)	8.0
	WNC*	4.7a (2.4)	9.8ab (1.8)	15.3b (0.4)	10.6
	MIDC*	5.8a (1.6)	9.9b (2.5)	14.0b (7.1)	8.2
	ENC	5.6 (2.9)	8.6 (8.6)	16.5 (10.7)	10.9
	ES	3.8 (1.5)	8.7 (3.5)	8.3 (0.4)	4.5
14	WS*	4.5a (1.6)	9.0b (1.7)	9.9b (1.6)	5.4
	WNC	4.8 (3.4)	10.6 (4.7)	17.2 (12.4)	12.4
	MIDC	6.2 (3.6)	11.6 (5.4)	14.5 (4.9)	8.3
	ENC*	4.2a (1.3)	8.7ab (3.3)	13.1b (6.9)	8.9
	ES	3.6 (1.3)	7.8 (3.6)	10.5 (3.5)	6.9
	FES	4.4 (0.7)	7.2 (3.0)	8.3 (1.0)	3.9
12	WS*	3.8a (0.5)	7.0ab (2.3)	9.4b (0.9)	5.6
	WNC*	4.6a (0.5)	8.6ab (1.0)	18.1b (12.6)	13.5
	MIDC	7.0 (3.6)	10.9 (7.1)	19.0 (12.7)	12.0
	ENC	5.1 (3.0)	8.7 (3.1)	14.5 (4.9)	9.4
	ES	4.1 (2.2)	7.0 (2.7)	10.0 (1.4)	5.9

Note: WS = western shoal, WNC = western natural channel, MIDC = midchannel, ENC = eastern natural channel, ES = eastern shoal, and FES = far eastern shoal.

* Significant Kruskal-Wallis test, H(0.05,5,3,2) = 5.25.

** a,b--means with no letters in common are significantly different (non-parametric Tukey test, Q(0.05,3) = 2.394).

lower observed DO levels. Overall, near-field monitoring suggested that dredge-induced DO reduction was minimal: generally less than 0.1 mg/ℓ with maximum mean reduction of no more than 0.2 mg/ℓ (Table 1).

Results of bay-wide monitoring suggested that the dredging activity resulted in slightly elevated turbidity (mean = 8.4 NTU, Table 3) and reduced DO saturation (mean = 11.4 percent, Table 2). As previously discussed, this drop in saturation represented a drop in DO of about 1 mg/ℓ (from about 7 to 6 mg/ℓ). While saturation levels rebounded after dredging ceased, turbidity increased. Elevated turbidity levels could be a function of the resuspension of fine-grained materials from the disturbed bottom in the wake of the dredge. The activity of a bucket dredge usually results in a pocketed bottom covered with a veneer of fine materials which could be easily resuspended by tidal or river currents.

A possible explanation for the concomitant reduction in DO could involve the scenario described in Model A, if the elevated levels of suspended material were organic (likely in the case of Haverstraw Bay sediments). The BOD resulting from the suspension of these materials would last only as long as new "unoxidized" materials were supplied and would, therefore, fall off after dredging ceased. Elevated turbidity could be expected to continue for a time after dredging ceased, until the bottom stabilized.

The results of this study suggested that the model of DO depletion, based on sediment concentrations of readily oxidizable compounds (ferrous iron, free sulfides), appeared to be a good predictor of DO reduction in the near-field around a bucket dredging operation. While predicted DO reduction was slightly greater than that observed, a liberal estimate of reduction is preferable, particularly in light of the highly variable conditions which characterize estuarine systems. While the model is simplistic, in that it requires few site-specific input variables, it provides a relatively accurate estimate of DO reduction. Since the basis of this model is similar to that which describes immediate oxygen demand (IDOD), field measurements of IDOD can replace measurement of iron and sulfide concentrations.

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